PECAN STREET

Accelerating Solutions for the Measurement and Verification of Soil Organic Carbon

A research and development roadmap with context on designing for adoption

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PECAN STREET

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I. Summary

Regenerative land management practices that build soil health transform agriculture from a global greenhouse gas (GHG) emitter to a global carbon sink and contribute to climate resilience. Rapid deployment of reliable and low-cost soil organic carbon (SOC) monitoring and verification (M&V) solutions, along with careful attention to the equitable design of carbon markets, will accelerate adoption of regenerative practices at scale.

Pecan Street's Digital Dirt program spent a year systematically seeking out the expertise of leading researchers and practitioners in soil science, big data, land management, carbon and ecosystem service markets, and social justice. This R&D roadmap summarizes key learnings, along with specific recommendations made by an interdisciplinary, multi-institution AI for Soil Carbon Measurement and Verification Working Group.

The Working Group determined that, while SOC sensor development is important and may eventually produce cost-effective solutions, near-term success can be achieved by improving existing agricultural models. The Working Group recommended immediate use of artificial intelligence (AI) and machine learning (ML) techniques to 1) integrate disparate data sources and 2) fill in missing input values to create a complete, high-quality test dataset. Results should be open-source and published on an open platform. This will drive innovation and promote equitable use by a broad mix of farms. Further, the Working Group urged moving quickly to use this test dataset to benchmark outputs from the three primary models currently used in agricultural planning —DSSAT, Day-CENT, and COMET-Farm — and where needed, to improve these models to reflect tolerance levels acceptable to carbon market managers. Work to implement these solutions has already begun.

The Digital Dirt team, along with collaborating researchers from Cornell University and Colorado State University, also advise thinking freshly about how farmers acquire knowledge and decide whether to adopt practices that build soil health and/or to participate in carbon markets. Understanding these differences is critical to ensure equitable access to potential soil wealth. It also opens up the possibility of motivating and reinforcing collaborative action at regional scales to maximize environmental, economic, and social benefits of regenerative agriculture.

II. Background

The Climate Opportunity

The Food and Agriculture Organization of United Nations (FAO) reports that agriculture, including activities within the farm gate and land use changes, represent about 20% of global greenhouse gas emissions (FAO, 2021). According to the Environmental Protection Agency (EPA), agriculture was responsible for 10% of GHGs in the US in 2019, 55% of which were related to soil management practices (EPA, 2021). Fortunately, carbon and nitrogen — the two GHG emissions that result from crop production — are important soil nutrients. Increasing carbon and nitrogen content within the soil, at the right levels of balance, increases soil health and fertility and has the added potential benefit of reducing atmospheric GHGs. Cropland soils are believed to hold the potential to sequester between 0.90 and 1.85 Pg C/year, which could provide 10% of the world's Paris Climate Accord emission reduction commitments (Zomer, 2017). At less than $10 per megagram of carbon dioxide equivalent, this is considered a low-cost pathway. Supporting farmers in the the transition to regenerative farming requires monetizing the value of the environmental services that it provides. Carbon markets could provide a viable economic pathway for farmers to be compensated for carbon sequestration.

Additionally, there is significant, pent-up customer demand for 'climate-beneficial' food and fiber products, similar to organic, free-range, grass-fed product offerings. And there is an opportunity for movement by leading corporations to reduce Corporate Value Chain (Scope 3) emissions that could provide added revenue for implementing practices that sequester carbon.

The Economic Opportunity

Enabling more farmers to get paid for environmental services such as carbon sequestration, and do so with increasingly profitable practices, is a critical intervention into the domestic agricultural sector. A pre-pandemic report by the Farm Bureau in October 2019 stated, "Chapter 12 farm bankruptcies continued to increase as farmers and ranchers struggle with a prolonged downturn in the farm economy that's been made worse by unfair retaliatory tariffs on U.S. agriculture as well as two consecutive years of adverse planting, growing, and harvesting conditions. Over the prior 12 months, Chapter 12 bankruptcies totaled 580 filings and were up 24% from the previous 12 months." (Newton, 2019)

Transparency in data, modeling outputs, and soil health will enable carbon markets to operate with more assurance of outcomes and therefore less risk. The current lack of verifiability and validation of carbon sequestration outcomes is leading most carbon markets to deliver only approximately 30-40% of the value of purchased offsets to the farmer. The bulk of the offset value is used for two purposes. First, to compensate offset project aggregators. Second, to establish offset reserves that can be utilized if projects under-deliver on soil carbon sequestration. Models that are easier to utilize, validate, and audit should lower the project aggregator costs, freeing up more value to be delivered directly to farmers and ranchers. Models that are validated and benchmarked will provide more certainty to markets and should result in lower offset reserves, again enabling more of the value of each offset to flow directly to farmers and ranchers. More income to farmers and ranchers for participation in regenerative agriculture programs and less of their time required to participate, will result in a higher transition rate to climate-beneficial land management practices.

Education and engagement with agricultural funders and industry leaders on open data standards, privacy best practices, and carbon market development will help to ensure that those most affected by these decisions are involved in making them.

The Measurement & Verification Challenge

To participate in carbon markets, a farm needs to produce an auditable, verifiable account of the baseline level of SOC on the farm and the additional carbon sequestered over time in the soil. Acceptable practices for measurement and verification must be codified in carbon marketplace standards to ensure compliance. Carbon credit standards for carbon sequestration on farms and ranches have begun to emerge over the past year. A July 2021 report by Environmental Defense Fund (EDF) and the Woodwell Climate Research Center analyzes where these codes can be standardized and improved to provide greater certainty to financial markets and to farmers (Oldfield, 2021).

Currently, most farmers, seeking verifiable measurements of their soil carbon content, get information the same way they've been doing it for decades. They take a one-cup sample of soil and mail it to a lab that sends them back a result. Collecting these samples manually is arduous and the cost per SOC test ranges from $12 to $32 per sample. Therefore, farmers limit their sampling and apply these point-source measurements to an entire field area. These measurements provide a good baseline that farmers can use to guide their land management decisions around fertilizer and other soil inputs, but the results are insufficient to provide market confidence or to show compliance with carbon market standards.

Low-cost, in-situ soil sensors that could provide high-fidelity, time-series, geospatial data on soil carbon are still only in the early stages of development. The sensors that are available in the marketplace almost all rely on near-infrared (NIR) spectroscopy. Their accuracy is variable, and they are not sufficiently cost-effective to return a profit within the carbon marketplace, which currently sells carbon offsets for an average of $15 per metric ton, equating to a potential payout of $30 per acre.

Most carbon markets and certification programs rely on a combination of modeled estimates and ground-truth data from lab-tested soil samples. These models are typically referred to as 'process models' and were developed decades ago for agricultural yield and farm planning. The three most common models are DayCENT and DSSAT, along with COMET-Farm/COMET-Planner (model and web interfaces that builds on DayCENT with a specific focus on helping farmers understand how to modify their practices to reduce GHG emissions). These models are built on open platforms and are free to researchers as well as farmers. The models are extended by soil scientists and agronomists as needed when new discoveries about soil, plant innovations, or data become available.

The models require a diverse set of input data, ranging from soil characteristics to agricultural practices, crop details, weather, and geophysical factors. For example, a user running the DSSAT model might need to enter over 200 data points. COMET-Farm requires 20 years of land management details. This depth and breadth of data can pose time and expense challenges as much of the information may not be directly accessible by the person using the model.

Because soil carbon and nitrogen are important soil health indicators, these models can estimate soil carbon increases or decreases that would result from changes to cropping and land management practices. The accuracy of these estimates is only as good as the data used to calibrate the models for each farm, and they often require a sophisticated understanding of the model to be correctly used. Most farms lack the adequate historical and soils data necessary for high-quality model calibration. Critically, research is lacking on how missing or estimated data for each model input impacts the accuracy of soil carbon and nitrogen estimation.

Without widespread availability of affordable ground sensors and constraints on the frequency and number of soil samples a farmer can afford to undertake, the best near-term option for widespread M&V of soil carbon sequestration is the available process-based models. While these models provide a useful, free tool for farm assessments, lack of benchmarking and complexity of data inputs limit how quickly and aggressively carbon markets for farmers and ranchers will grow. Investments in improving the ease of use and establishing certainty parameters by benchmarking the accuracy of model output against high-fidelity field measurements are critical for expanding regenerative agriculture as a preferable economic option for farmers and ranchers around the world.

A Public-Private Sector Approach to the M&V Challenge

In 2020, Pecan Street collaborated with the Texas Advanced Computing Center (TACC) at The University of Texas at Austin to convene an interdisciplinary working group to map an open-source approach for solving the M&V challenge that would be responsive to the needs of both farmers and managers of emerging carbon markets. A key part of the Working Group's mission was to gauge if AI and ML applications have potential to produce leapfrog solutions.

Table 1: AI for Soil Carbon Measurement and Verification Working Group Participants

Name	Organization	Title	Expertise
Dr. Eric Slessarev	Lawrence Livermore National Lab	Research Fellow; ISCN's Soil Health Coordinator	Soil Scientist; Modeling Expert
Dr. Kathe Todd Brown	University of Florida	Assistant Professor, Environmental Engineering Sciences; ISCN's Data Coordinator	Soil Scientist; Modeling Expert
Dr. Dan Harburg	IndigoAG	Vice President of Innovation, Carbon	Carbon Markets Expert
Kenneth Walker	GSI Environmental Inc.	Lead on SOC measurement team for BCarbon	M&V Standards & Protocols for Carbon Offset Market
Dr. Paul Navratil	TACC	Director of Visualization	Data Management & AI; Project Lead
Stefan Jirka	Verra	Innovation Manager, Agriculture	Carbon Markets
Dr. Kenneth Medlock	Rice University	Professor, Energy & Resource Economics	Carbon Markets & Economics
Dr. Nithya Rajan	Texas A&M	Director, Rajan Lab; Associate Professor, Soil and Crop Sciences	Soil Scientist
Dr. Johannes Lehmann	Cornell University	Professor, Soil Sciences & Agroecology	Soil Scientist
Dr. Pramod Pokhrel	Texas A&M	Postdoctoral Research Associate, Rajan Lab	Soil Scientist
Dr. Matthew Smith	Agrimetrics	Chief Product Officer	Data Management; ML
Dr. Weijia Xu	TACC	Research Engineer; Manager, Data Mining and Statistics	AI / ML and data for public good
Dr. Zhao Zhang	TACC	Research Associate; Data Mining & Statistics	AI / ML and data for public good
Dr. Marc Boudria	Independent	Independent	AI / ML

Over the past decade, ML and AI have grown in their sophistication and impact as the amount of data collected on people and industries grows. Other sectors (e.g., biomedical research, satellite management, and object detection) have proven that when fed with enough data, AI carries the potential to solve problems and detect connections that are beyond human capabilities. However, AI technologies behave very differently than traditional analytical and computational approaches. Effective application in the agriculture sector depends on marrying the domain expertise of AI developers with that of soil scientists

The Working Group met over a 6-month period to exchange perspectives on the following core questions and to discuss domain-specific challenges and best practices to see if ML and AI approaches could impact the M&V effort:

- Do AI advances have the potential to unlock verifiable, accurate proxy measurements for SOC content and/or accurate predictions of SOC changes over time due to specific farm management practices and/or other factors, such as weather and soil typology?
- Are there sufficient data on soils and farm practices from the USA to enable application of ML and AI? Where insufficient datasets are identified, can AI/ML applications produce useful synthetic data or analytics capabilities with existing measurements to produce new insights into previously impenetrable phenomena? Can the results be verified against real-world data and used to transform or benchmark the accuracy of existing SOC models?
- What data sources can be combined to fill known gaps, and what can we learn from them?
- What ML or AI approaches are best suited to developing solutions for proxy or remote SOC sensing? What ML or AI solutions are best suited to developing predictive algorithms for SOC changes over time?

III. Roadmap for Open Data and AI for Soil Carbon M&V

In its 6-month convening, the Working Group achieved consensus on several conditions that will shape the solutions required to resolve the M&V challenge, including:

A. Highly accurate, in-field baseline measurements through soil sampling or a proven sensor combined with predictive models based on existing open-source agricultural models, such as DSSAT, DayCENT and COMET-Farm, are the best option to estimate carbon credit generation over the lifespan of a carbon credit project for regenerative agriculture.

B. Ground-truth measurements of SOC content at five-year intervals combined with market tools such as a "reserve fund" to accommodate known measurement and prediction model uncertainties is recommended for verification and offset production risk management.

C. Combining models and SOC ground-truth data reduces the need for total ground-truth data from yet-to-be-developed sensors or proprietary M&V systems.

D. M&V of SOC accumulation for the top 30cm of soil testing is adequate, especially in light of the lack of consensus of critical dynamics among soil scientists down to one-meter depths.

Given the central role that SOC models have in A, B and C, the Working Group first recommends a three-step R&D roadmap to tackle the SOC data gaps that are limiting the ability to benchmark and/or improve existing SOC sequestration models. Each of the following steps are discussed in more detail below:

1. Curate open soil health and SOC datasets and make them accessible to researchers and entrepreneurs
2. Develop a repeatable knowledge extraction/mapping process to create an integrated soil data system that facilitates the movement of future heterogeneous datasets into a homogeneous dataset.
3. Develop and verify the reliability of models to enable coarse/remote sensing measurement to infer more granular values based on small samples so that time- and cost-efficient new methods can be used to fill data gaps.

Step 1: Open Datasets

The Working Group identified the following five publicly available data sources to serve as the backbone of an integrated soil health and carbon dataset for agricultural model evaluation and calibration. Pecan Street negotiated access to these datasets, transformed them for ease of comparison, and integrated them as individual files in our online researcher database Dataport (www.pecanstreet.org/dataport).

1 — National Cooperative Soil Survey (NCSS) Soil Characterization Data

The NCSS dataset contains soil characterization data from the National Soil Survey Center (NSSC), Kellogg Soil Survey Laboratory (KSSL), and cooperating laboratories. The dataset contains soil samples taken from soil sites primarily based in the United Stated but includes samples from other countries. Sites are identified by unique site identifiers. A site may have one or more pedons of soil profiles. Soil samples analyzed at a NCSS laboratory include soil properties such as bulk density, particle size distribution, and pH.

2 — Soil Survey Geographic Database (SSURGO)

The Soil Survey Geographic Database (SSURGO) contains data collected by the National Cooperative Soil Survey over the course of a century. This dataset includes data from the United States and the Territories, Commonwealths, and Island Nations served by the USDA-NRCS. Examples of information available from this dataset includes water capacity, soil reaction, electrical conductivity, and frequency of flooding; yields for cropland, woodland, rangeland, and pastureland; and limitations affecting recreational development, building site development, and other engineering uses.

3 — SOils DAta Harmonization (SoDaH) & Synthesis Database

The SoDaH database contains data from 215 locations and 186 unique study sites. Data for this dataset is contributed from Detritus Input and Removal Treatments (DIRT), the Nutrient Network (NutNet), Long-Term Ecological Research (LTER) Network, National Ecological Observatory Network (NEON), and Critical Zone Observatories (CZO) networks.

4 — e-RA Rothamsed Archive—Broadbalk-Rothamsted Long-term Experiments

The Broadbalk Experiment Data from the e-RA Rothamsted Archive is one of the oldest continuous agricultural experiments in the world. The objective of the experiment is to test the effects of different organic manures and inorganic fertilizers (N, P, K, Na and Mg) on the winter wheat yield. The experiment site has a control strip that has not received organic manure of inorganic fertilizer since 1843.

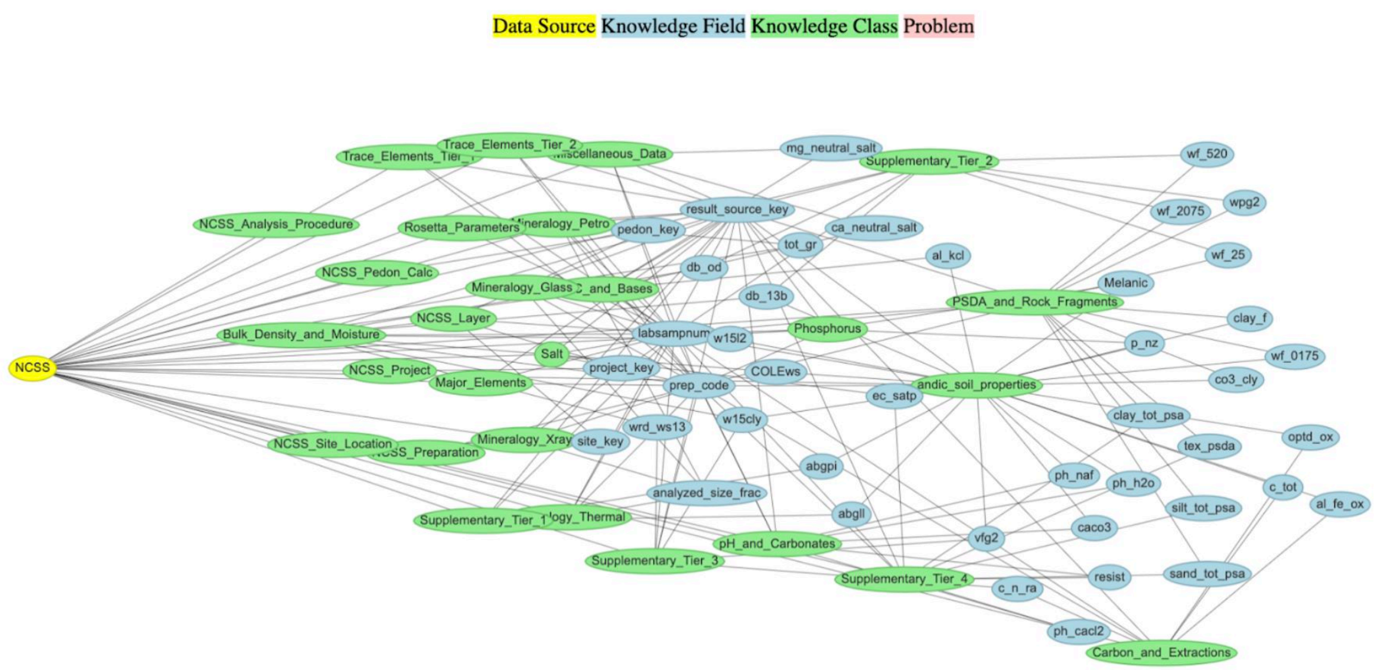
5 – Weather Database

The weather data is provided by Dark Sky. Data points including temperature, dew point, humidity, air pressure, wind speed, cloud cover and precipitation are provided. The dataset provided contains data for all NCSS site locations from 2016 – 2020. However, researchers interested in using data for additional site locations or other years can use the Jupyter Notebook the team created to help pull weather data. The Jupyter Notebook was used to help the team narrow down the 285 unique locations where the weather data needed to be collected to cover thousands of unique NCSS site locations.

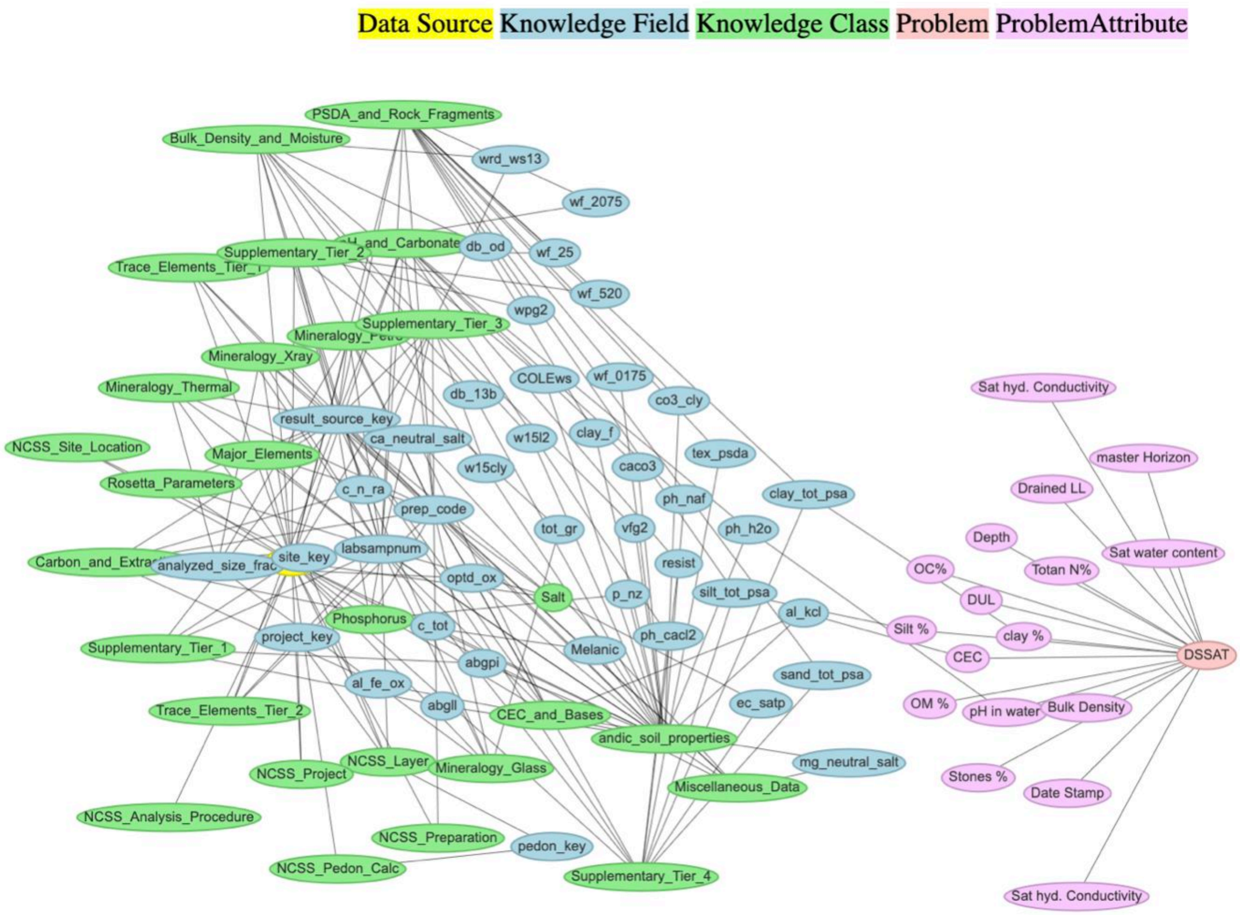
Step 2: Knowledge Mapping Process

TACC has begun combining the datasets into an integrated data system. The complexity of this task is significant as the datasets contain some overlapping data and some non-overlapping data, most of which contains different labels and data structures. As a first step in the integration process, TACC is applying a unique ML-approach to map each dataset into a common structure, utilizing a combination of an established ontology and an embedded ontology that is revealing itself as the datasets are combined.

The figure below represents the process of mapping the NCSS dataset using a knowledge graph representation. To illustrate the power of this approach, the team mapped "Classes" and "Fields" required for the specific use case of running the DSSAT model, which in turn can be replicated for DayCENT and COMET-Farm. Using a knowledge graph approach allows for integration of domain ontologies and diverse data sets. It is expandable for additional use cases, and provides strong foundation to employ AI/ML techniques for SOC M&V.



As expected, a single dataset does not have sufficient content to support running models such as DSSAT, DayCENT or COMET_Farm. In the below figure, the NCSS dataset is mapped to the required data inputs for the DSSAT model, showing that much of the dataset is not relevant and many of the needed inputs are not available.



As such, datasets 2-5 in the list above, as well as additional data from the USDA Long-Term Agricultural Research projects that the team hopes to gain access to, will be similarly mapped to enable easy comparison and selection of available data for specific objectives.

The results of this work will be published in an open repository by Pecan Street and TACC. The datasets are available on Pecan Street's Dataport as individual files at www.pecanstreet.org/dataport. The integrated data system will be made available through TACC as additional funding is secured to complete development of the homogenization ML process.

To ensure scalability of the dataset and replicability of the approach and schema, the research team will build on existing ontological standardization efforts to establish an ontology for the benchmark dataset by:

1. Mapping existing data elements' relationships and naming conventions, and working with domain experts to resolve conflicts and propose a collective naming convention
2. Accommodating nuances required by the DSSAT, DayCENT, and COMET-Farm models
3. Circulating to various stakeholders to gain feedback and iterate the proposed ontology until sufficient agreement is reached.

Throughout these efforts, the Working Group further recommends continued collaboration with other industry leaders and researchers to:

- Establish a recommended data ontology standard for soils
- Create a data reporting and database architecture schema to standardize future soil datasets
- Create a data documentation guide to support non-soil scientists in working with the soils data for AI, model, and soil carbon market innovations
- Establish a set of open APIs that facilitate researcher integration of datasets to facilitate scientific discoveries.

The ontology TACC is using and the one that is de facto embedded in the current datasets represents historical understanding of soil science. It is somewhat time stamped based on when the dataset was started. The global soil science community is working together to create a new ontology based on modern insights and understanding. Dr. Kathe Todd-Brown is co-leading the international collective to spearhead these efforts. Once a standardized ontology gains acceptance, which represents a massive and significant undertaking, we can graft the combined dataset produced through this R&D roadmap onto it.

Step 3: Data-Model Integration and Benchmarking

Since using the main SOC models is complex, the Working Group recommends providing an easy way for a farm to validate it has set up the measurement model correctly. To do this, the team should aggregate and standardize current, publicly available datasets such that a highly accurate open test dataset can enable users of the DSSAT, DayCENT, and COMET-Farm models to validate their set up of the respective model before using it to perform M&V on their own property. In response, Pecan Street and TACC are pursuing funding to:

1. Identify data gaps in the combined dataset versus what each model requires and either:
   A. Use existing ground-truth measurements to train ML models to create synthetic data, or
   B. Identify alternative sources for data elements such as remote sensing via satellites, drones, fixed machine vision-enabled devices; or other such proxy measurements to backfill those data gaps.
2. Characterize DSSAT, DayCENT, and COMET-Farm model outputs using benchmark data against key usability metrics such as accuracy, precision, error ranges, etc. and confirm adequacy with carbon market participants.

The Working Group estimates that the essential Steps 1-3, as outlined above, can be accomplished in 18 months if adequately resourced. All work and outputs will be open platform and open source, helping to ignite innovation and market confidence in the outcomes.

Case Study: DSSAT Validation Experiment

To understand what data is required to calibrate and run a standard agricultural model, Pecan Street undertook an accuracy validation experiment with researchers from the Rajan Lab at Texas A&M University. The process of using the DSSAT to model the SOC content changes that would occur under different land management practices informed the database architecture currently under development at TACC for the open, integrated dataset.

To carry out this analysis, Dr. Rajan and a post-doctoral fellow, Dr. Pramod Pokhrel, identified two long-term experiment sites run by Texas A&M researchers. The data from these fields were utilized to construct a DSSAT model of the fields (one which is tilled and another that is not tilled to understand fit with this critical regenerative agricultural practice), which then estimated what the SOC levels at varying depths in the soil should be. These estimates were compared against soil samples collected by Dr. Pramod on the fields. The model results for estimates of SOC were then compared to real measurements to gain an assessment of the model's accuracy. In summary, the study, which will be published in full on Pecan Street's website, found that the measured SOC in no-tillage management were 1.26%, 0.79%, and 0.74% on top 5cm, 10cm, and 20cm, respectively. DSSAT estimated SOC was 0.99% in the top 20cm of soil. The comparative assessment found that the estimated SOC value produced by the DSSAT model (specifically, the CENTURY-Parton module of DSSAT) was 6% higher than the measured SOC. In the conventional tillage experiment, the measured SOC was 0.88%, 0.72%, and 0.63% at 5cm, 10cm, and 20cm depths, respectively. However, DSSAT estimated 0.99% SOC in the top 20cm of soil.

Soil samples were also taken from the winter wheat – soybean rotation plots in 2002 and 2015. In 2002 with no-tillage management SOC was 1.68%, 0.89% and 0.80% at 5cm, 10cm and 20cm depths. The SOC content was lower in conventional till plots with the value of 1.12%, 0.87%, and 0.68% SOC at three depths. Overall SOC amount decreased slightly in 2015 in both tillage management approaches and depths of measurement. In no-tillage management, SOC was 1.48%, 1.12%, and 0.69% at 5cm, 10cm, and 20cm depths whereas it was 1.01%, 0.96%, and 0.69% with conventional tillage. The DSSAT simulation experiment estimated 0.99% SOC in 2002 and 1.06% SOC in 2015 under no-tillage management. Similarly, the estimated SOC values were 1.00% in 2002 and 1.03% in 2015 with conventional tillage.

The overall result shows that the DSSAT SOC estimations had good agreement with the no-tillage management data but over-estimated SOC for the conventionally managed site. A study in the European Journal of Soil Science has also reported that DSSAT estimates tended to overestimate SOC in conventional tillage management (Nicoloso, 2020). Many factors affect soil organic carbon such as initial soil organic carbon, soil type, amount of residue, and tillage. The difference in observed and estimated SOC may have been due to the factors that limit the amount of biomass produced and its incorporation. The research also found that mono-cropped production farms in the process of transitioning from conventional tillage to a no-till approach had a net decrease in SOC compared to farms that continued to practice conventional tillage within Texas or farms that transitioned to no-till in conjunction with integrated farming practices. This report points to the need for additional research on practice-SOC relationships and model variables and metrics.

The results of this initial assessment reveal that even when complete land management and soil data are available to calibrate the DSSAT model, its estimations, while close to actual measurements, have an error margin, proving out the need to benchmark these models with proven data and to undertake a sensitivity analysis that can drive strategic investments in high-fidelity measurements versus low-cost estimations.

IV. Incremental Momentum-Building R&D Activities

Pecan Street's Digital Dirt team builds on the Working Group's recommendations with suggestions for three areas where additional R&D would expand the utility of and build confidence in model-based soil carbon M&V. The sensitivity analysis, farm-level benchmarking, and sensor development described below can happen in parallel with the three-step process recommended by the Working Group.

Sensitivity Analysis for Model Improvement

To improve the existing models, users need to understand how inaccuracies or incompleteness in data for each model input variable impacts the accuracy of outputs. This research has yet to be comprehensively undertaken in relation to soil carbon and nitrogen content outputs of the models. To close this knowledge gap, a sensitivity analysis by variable for the different soil and climate zones for each model should be undertaken to identify where investments should be made to improve model accuracy and cost and recommended mechanism (e.g. high fidelity in-field measurement, remote sensing, remote imagery, synthetic data) of data acquisition for valid estimates, predictions, and verification. A sensitivity analysis is also an important step to simplifying the gathering of model inputs for farmers to use in estimation of their potential for SOC sequestration in transitioning to regenerative farming practices.

Farm-Level Model Benchmarking

Having a benchmark dataset for a farm to use to confirm its set up of the SOC model provides additional benefit because various carbon markets standards, such as Verra Carbon Standard, require independent audit of modeled estimates. This adds to cost and time, which puts pressure on profitability for the farm to participate in carbon markets. Auditors review the underlying calculations and reasonable certainty of the modeled results for each project. An open, transparent benchmark dataset that can be tailored for model calibration to specific farms or could be run through a model and compared to the outputs of the project model as an accuracy comparison is a valuable capability in attesting to a carbon credit's validity. This would reduce auditor review time and costs.

Soil Sensor Development and Validation

The outcomes of the model sensitivity analysis, described above, will reveal which modeling inputs require high-fidelity measurement and which inputs can be developed using estimations or synthetically generated data. Those inputs that are found to drive model sensitivity for SOC content may be worth investment in solutions to produce this data with high accuracy.

As public sector and philanthropic investments into sustainable agriculture grow, entrepreneurs will increasingly be drawn into this space with innovations that fuel market growth. The most critical of these innovations right now is the development of low-cost, high-fidelity sensors or proxy measurements that can sample SOC, as well as nitrous oxide emissions over time. There are already several notable entrants into the soil monitoring sector with a variety of product applications that range from near and mid-infrared radar sensors to AI-based soil probes. However, the industry currently lacks an objective and trustworthy third-party product validation service that can provide insights into the accuracy and reliability of these products – specifically AI/ML models at the core of translating sensor inputs to relevant data streams for the SOC models. The proprietary nature of this intellectual property, which these AI/ML models represent, can be maintained given various approaches already proven in the broader cleantech sector as is has leveraged national labs or other notable non-profit organizations to play this role. A similar product performance validation center at USDA LTAR stations would expedite market adoption of these products and increase the efficiency of carbon markets for farmers.

V. Designing for Adoption

Pecan Street's Digital Dirt program collaborates with researchers from Cornell University, Colorado State University, and other institutions to understand how farmers learn about, invest in, and adopt innovations. From this work, we have identified three essential strategies that must be addressed in parallel with the Working Group's recommendations for M&V development:

1. Co-design solutions with a diverse mix of farmers and agriculture industry participants
2. Identify effective channels to promote the innovations to foster equitable benefit
3. Build adoption by clusters of farms to realize landscape-scale benefits.

Building What Farmers Want and How They Want It

To develop a better understanding of how to support farmers in changing their land management practices, Pecan Street's Digital Dirt team undertook an initial survey of 79 farmers across New York and Texas (www.pecanstreet.org/farmersurvey/). One of the questions asked farmers to rank six factors they considered most important or valuable in making decisions about farm management: profitability, ease and time efficiency, soil health, farm worker and community health, government incentives, and novelty and/or personal interest.

For New York and Texas farmers, profitability and ease and time efficiency rank as the most important factors while government incentives rank as least important. When asked how they evaluate a potential farm management practice change, the words time and cost are the most prevalent in the responses.

As such, the resulting benchmark datasets, characterized SOC models, and the means to access them, should be designed for quick, easy use by farmers. Developers must be attentive to collecting input early and iterating based on the real world experience of an economically, demographically, and culturally diverse mix of farmers, representing use cases that encompass a broad mix of geographies, crops/livestock, and farm sizes. Equally, it will be important take into account when and for what purposes farmers prefer to test out emerging resources with support from communities of place (i.e., neighbors and extension service agents) versus when they would turn to emerging communities of practice, including online forums and social media, for advice on available resources and how to use them.

The Equity Challenge

The history of racist lending and land ownership policies in the United States, which prevented individuals of color from owning land and resulted in the theft of their land, continues to systematically bar people of color from farming and ranching. Further, the economics of food and the high cost of productive land make it extraordinarily difficult for an individual without independent wealth to acquire land for food production. In Pecan Street's recent farmer survey, nearly 88% of the respondents identified as Caucasian. Nearly half of the respondents to the survey reported that they grew up on a farm, and 87% plan to leave their farm or ranch to family members. The racial disparities are set to propagate for another generation.

Compounding the situation, as farm lenders move towards incorporation of increasingly common soil health data in their risk assessment and property valuation, and other means of accessing capital come online, ensuring equitable access to information and land management technologies will be important to help undo system racism within land ownership and agriculture.

Driving Equitable Adoption

Historically, the model for disseminating agricultural innovations has relied on university extension services, local governmental efforts, and industry participants. However, given the legacy of racist and otherwise biased policies, lending practices, and business tactics embedded in many of these structures, BIPOC, LGBTQIA, and female-identifying farmers have been significantly excluded from being proactively targeted for adoption of prior beneficial innovations.

In Pecan Street's survey, most respondents reported that their primary source of information about new technologies, research, or funding came from neighbors and other farmers/ranchers in their communities, with about one third of respondents also reporting that farmers' associations and local extension agencies were important sources of information. Given the large influence of social networks on a farmers' access to information and resulting opportunities, gaining an understanding of how those social networks and information channels differ for farmers and ranchers of color is necessary to ensure equitability of opportunities and access to resources. Pecan Street's farmer survey, and other similar sector analysis, also reveal that access to land and financing are more challenging for individuals of color.

Additional research can illuminate where farmers of color and other historically marginalized groups, as well those innovating from the edge such as urban farmers, go for technical information and tools, how they give voice to their own experiences, the factors that shape decision-making at the individual farm and community scales, and the practices they employ for healthy land management. We need to understand how these pathways may differ from white, male farmers and whether structural impediments prevent access to tools or financial resources. Best practice guides, resource maps, and information sharing platforms must be developed in close collaboration with these users.

As a first step, Pecan Street is developing a research project to illuminate information and resource access differences patterned along racial and gender lines. Part of this work will involve surfacing recommendations for community-based resources that need to be created or modified. Legacy theories of early adopter-based change focus on targeting R&D

results and access to new resources to those individuals who already have the time, financial resources, and connections to identify and invest in new technology, which is yet another structure that perpetuates inequalities. As such, Pecan Street is seeking alternative theories of adoption, which better fit with realities of historically bypassed farmers.

Building to Landscape-Scale Impact

The environmental impacts from practice choices made by farmers do not stop at their fence lines. There are few examples of coordinated landscape-scale farmland management based on shared socio-ecological goals (Jellinek et al. 2018), but past work in the bioenergy space demonstrates that community-scale assessments reveal new opportunities for landscape design in addressing climate change issues. Similar strategies could be employed to produce greater aggregate soil carbon sequestration than is possible simply by optimizing management practices of individual farms (Field et al. 2018; Mishra et al. 2019).

While the social analysis of collaborative, regenerative farmland management has been limited, we see important evidence of a "soil stewardship ethic" and emerging interest from individual farmers in soil health enhancement as an adaptive response to changing climate (Roesch-McNally, Arbuckle & Tyndall 2017). Equally, we are encouraged by successful examples of collaborative community management and monitoring of carbon storage in the context of forest protection—where the carbon storage is readily visible as aboveground biomass (Larrazábal et al. 2012). There is potential to make soil carbon sequestration tangible to farmers with more transparent, convenient monitoring tools and data to support development of markets that leverage community-scale action.

A key benefit of shifting to community-scale is that it side-steps scientific unknowns related to soil carbon sequestration such as transferability of SOC between geospatial carbon pools. A farm-level approach does not account for how much carbon accrual in soil occurs due to atmospheric drawdown or from homeostatic or other chemical processes that draw carbon from other regions of soil into the area under regenerative farming. Community-scale initiatives resolve this issue if sufficient participation is achieved from neighboring farms.

VI. Conclusion

AI/ML techniques have tremendous potential to produce the viable, near-term M&V solution. Combining this technology-focused R&D effort with careful attention designing for equitable adoption can dramatically accelerate the transition to regenerative agriculture. There is an actionable path to achieve the promise of soil carbon sequestration as a climate solution.

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